Data assimilation for the investigation for temperature variations in the Paris Basin and the Netherlands

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ABSTRACT

Deep geothermal energy systems, intended mostly for the direct use of heat, have been attracting increasing levels of interest in the past 10 years in Western Europe. Both in the Netherlands, where the sector took off with the first system in 2005, and in France, where there has been a resurgence in interest after a 20-year gap, geothermal energy is seen as a key player for a sustainable future. To support the development of deep geothermal energy systems, the scientific community has been working on tools that could be used to highlight areas of potential interest for geothermal exploration. In the Netherlands, ThermoGIS is one such tool that has been developed to inform the general public, policy makers, and developers in the energy sector of the possibility of geothermal energy development. One major component incorporated in this tool is the temperature model.

For both the Netherlands and the Paris Basin (the northern basin in France, which has proved to be of particular interest for the development of geothermal energy), we created thermal models at the lithospheric scale that focus on the first few kilometres of the subsurface for deep geothermal exploration. This regional thermal modelling concentrates on the variations of geological thermal conductivity and heat production both in the sediments and in the crust. In addition, we carried out special modelling in order specifically to understand convectivity in the basin. This modelling focuses on variations at a regional scale. At this scale, the aim of this work is to build on these models and, using data assimilation, to discriminate in the actual causes of the observed anomalies.

The temperature results obtained for the Netherlands show some thermal patterns that relate to the variation of the thermal conductivity and the geometry of the sediments. There is also strong evidence to indicate that deep convective flows are responsible for thermal anomalies. In the Paris Basin, the thermal conductivity has a distinctive impact on the thermicity but the deeper anomalies are impacted by the variations in thermal conductivity and radiogenic heat production in the pre-Mesozoic.

1. TEMPERATURE MODELLING AND GEOTHERMAL ENERGY EXPLORATION

The investigation of geothermal energy in sedimentary basins requires a good understanding not only of the structure and composition of the basin considered but also of its evolution (Cloetingh et al., 2010). An important parameter to identify suitable geothermal energy systems is the temperature. The primary access to temperature information in basins is granted through the wells. For a large-scale investigation, the large amount of temperature data required is given by oil and gas exploration and production wells. To go further in the process of understanding the thermicity in the basin, and to have a complete vision in 3D, we developed a tectonic-heat flow modelling methodology that has enabled us to consider the geology at a lithospheric scale with a specific focus on the upper 10km.

To integrate to take account of all the variability that is inherent to geological structures, the integration of data is an important aspect. Our aim was to arrive at a complete vision of complex processes, and to achieve this, we combined two approaches: the integrative and the specialised methods. In the integrative approach, all parameters are included in a single model (van Wees et al, 2009) with the limitation that unusual thermal features remain uncharacterised. In the specialised approach, some specific thermal features are investigated so that we might understand temperature anomalies that cannot be explained by the general model.

Section 2 of this paper discusses the case of the Netherlands with a general model that has been achieved to understand the thermicity in the sedimentary layers. A case-study has been carried out on the Dinantian Cabonates, below the Noordoostpolder, exploring the misfit between the measured and modelled temperatures. Section 3 of this paper explores the thermicity of the Paris Basin in light of new studies made on the basement.

2. THE NETHERLANDS

The Netherlands has a basement that mainly consists of (Eastern) Avalonian crust (Pharaoh et al., 2010). The overlying sedimentary cover can be in excess of 8 km of thickness starting at the Devonian or Dinantian (early Carboniferous). The Late Carboniferous (Westphalian) is the most important part of the sediment thickness with several kilometres in certain sub-basins (e.g. the Western Netherlands Basin). For the purpose of our modelling, we have identified and described 13 sedimentary layers in the Netherlands. The temperature values have been collected in wells, giving a total of 1293 temperature points in the basin. The country-scale modelling (Bonté et al, 2012) used the geological description as well as the temperature values to obtain a 3D model of the temperature behaviour in the Netherlands and to investigate the thermicity in the Dinantian

2.1 Temperature modelling in the Netherlands: parameters and method

The modelling in the Netherlands is first of all based on the description of the 13 sedimentary layers from a geometrical and compositional point of view. The geometry is given by the digital model available on the nlog website (www.nlog.nl) and the composition has been defined based on the literature (mainly Wong et al, 2007). **Table 1** describes each of the 13 layers considered. For each layer, the lithology is defined by a mix of basic lithologies with predefined parameters such as the evolution of compaction, thermal conductivity, and radiogenic heat production. As our model considers the base of the lithosphere as a lower boundary, the lithospheric mantle, lower crust, and upper crust has been described for the same fundamental parameters required to build the thermal model.

The methodology only considers the conductive effects in 3D, considering the conductivity and heat production in the lithospheric mantle, crust, and sediments. The temperature at the base of the lithosphere is defined at 1330ºC.

2.2 Temperature modelling in the Netherlands: temperature dataset

The temperature values used in the Netherlands are typical and representative of the availability in sedimentary basins. They are of two types: Drill Stem Test (DST) and Bottom Hole Temperatures (BHT). The dataset collected is composed of 4276 BHT measurements in 456 wells and 52 DSTs in 24 wells. While the DST measurements can be used as they are collected, the BHT require a correction due to their method of acquisition. Two main types of correction are available for such large datasets: analytical and statistical. Several analytical corrections have been proposed throughout the last decades but according to the work of Goutorbe et al. (2007), the Instant Cylinder Source (ICS) method is the most reliable with a reasonable requirement to preform the correction. The result of the ICS correction of the BHT measurements (BHTx_ICS) is 412 values in 218 wells. To expend these datasets, we used the statistical AAPG method, described in Deming (1989), on the remaining uncorrected BHT measurements. The additional 829 BHT corrected using the AAPG method (BHTx_AAPG) are taken from 363 wells. The resulting dataset consists of 1293 values taken from 454 wells (**Fig. 1**), spread between depths of just a few hundred metres and over 5 km with a higher concentration in the West Netherland Basin and in the Groningen and Friesland Platforms.

2.3 Temperature modelling in the Netherlands: modelling results

The model is presented in iso-depth slices of the resulting 3D cube (**Fig. 2**). The temperature results obtained show a strong impact of the variation in the lithology through the thermal conductivity. As expected, the Zechstein Group (Late Permian), which has a salt composition in the northern half of the Dutch territory, is responsible for the short-scale temperature variations due to the salt diapirs. The shally Altena Group (Early Jurassic) has a thermal insulating impact in the West Netherland Basin at 4 km.

Table 1: Sedimentary layers for the thermal model of the Netherlands.

Layer	Period	Age min.	Age max.	Average lithology
Quaternary	Quaternary	0	2.5	Fine- and coarse-grained siliciclastics
Upper North Sea Group	Cenozoic	2.5	20	Fine- and coarse-grained siliciclastics
Lower and Middle North Sea Groups	Cenozoic	20	61.7	Mainly coarse-grained siliciclastics
Chalk Group	Cretaceous	61.7	99.1	Limestone (chalk)
Rijnland Group	Cretaceous	99.1	145	Fine- and coarse-grained siliciclastics, marls
Schieland, Scruff and Niedersachsen Groups	L. Jurassic	145	163.4	Siliciclastics, bituminous shales, coal
Altena Group	E.-M. Jurassic	163.4	203.6	Marine shales and carbonates
Upper Germanic Trias Group	M.-U. Triassic	203.6	246.2	Fine-grained siliciclastics, carbonates and evaporites
Lower Germanic Trias Group	E.-M. Triassic	246.2	251	Fine-grained siliciclastics
Zechtein Group	Permian	251	258	Salt, carbonates and siliciclastics
Upper Rotliegend Groups	Permian	258	268	Coarse-grained siliciclastics
Silesian	L. Carboniferous	268	330	Fine-grained siliciclastics
Pre-Silesian	E. Carboniferous	330	360	Carbonates

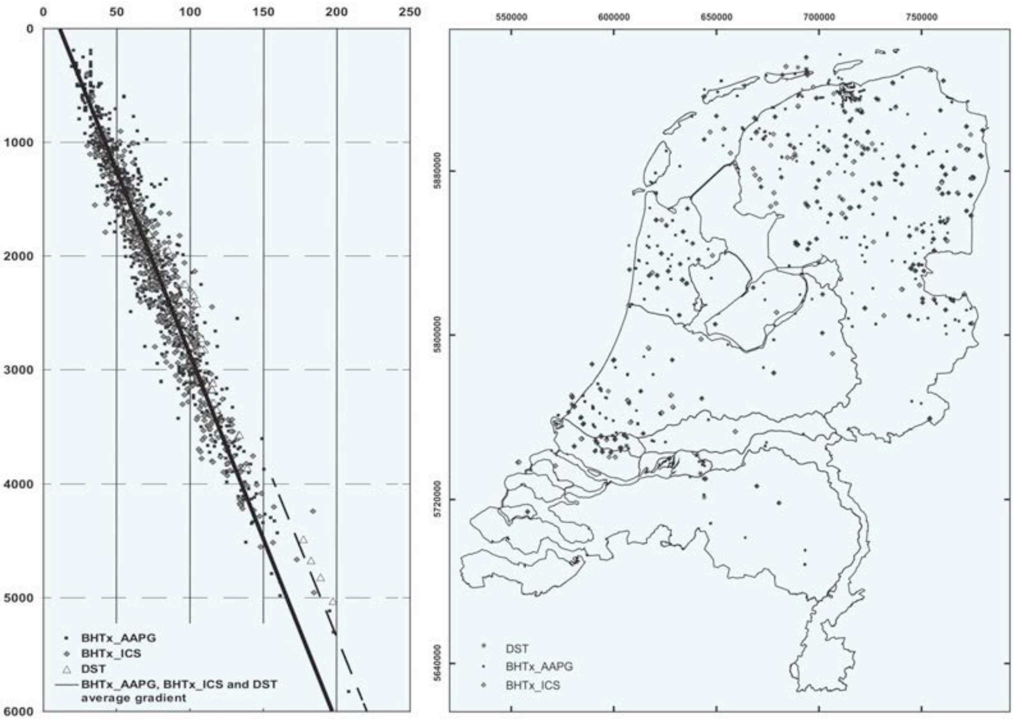

Figure 1: Temperature dataset in the Netherlands.

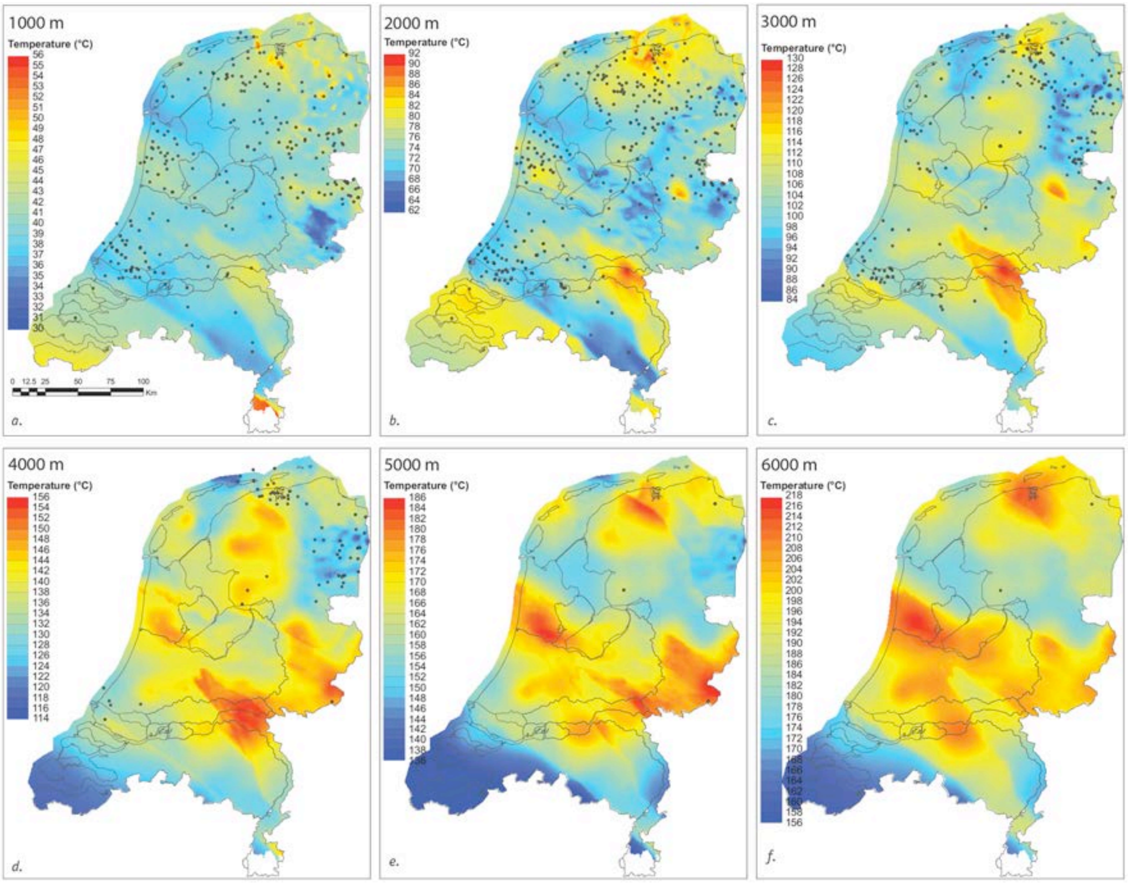

Figure 2: Modelled temperature in the Netherlands at six different depths.

2.4 Temperature in the Netherlands: convection in the Dinantian (Lipsey et al, 2016)

The comparison of the modelled temperature displayed in **figure 2** and the BHT and DST measurements in the Noordoostpolder shows a strong misfit below 4 km (**Fig. 3**). This misfit is believed to be created by a convective system. Lindsay et al. (2016) have modelled this thermal convection.

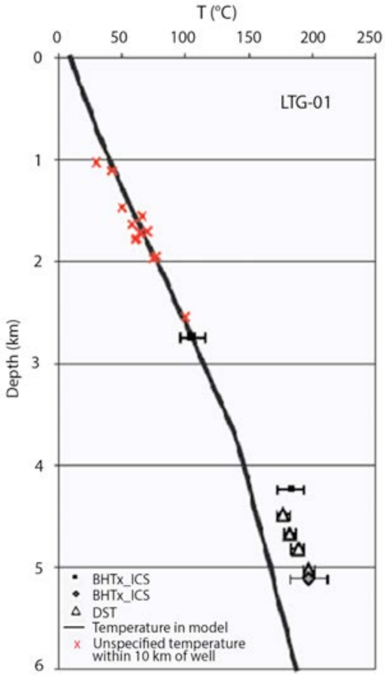

Figure 3: Comparison between the modelled temperature and the measurements in and around the Luttelgeest (LTG-01) well.

The logs and cores in the LTG-01 well describe the presence of limestone below 4355m. The seismic line that passes over LTG-01 (Fig. 4), clearly identifies the presence of a platform, with the LTG-01 well positioned on its edge.

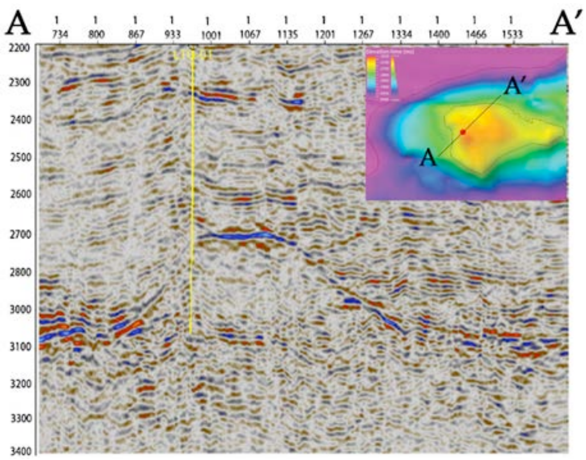

Figure 4: Seismic line SW-NE over the LTG-01 well

The modelling of the thermal convection is made on a simplified shape of the platform (**Fig. 5**).

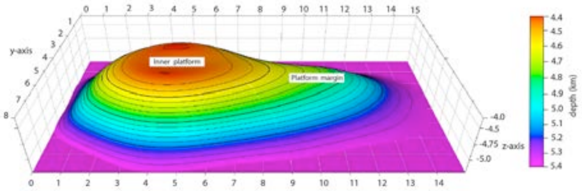

Figure 5: Simplified shaped of the modelled platform

Firstly, two variables have been tested: the shape of the platform (more or less flat) and a single permeability (2.10^{-14} and 6.10^{-14} m^2) for the whole platform. The results were not as conclusive as expected, with the gradient in the platform steeper than the measured values. Following this first model, the modelling investigates the sensitivity of the permeability structure by incorporating the heterogeneous nature of permeability between the inner platform and margin. The best result (**Fig. 6**) is given by model 3b, which has a permeability of 2.10^{-14} m^2 in the inner platform and 6.10^{-14} in the platform margin.

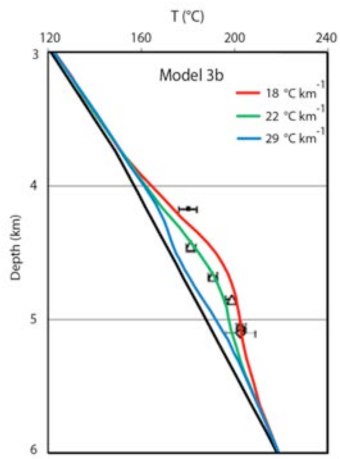

Figure 6: 1D result of the best fitted model (model 3b).

2.4 Temperature in the Netherlands: results and discussion

The results obtained by the regional scale tectonic-heat flow modelling in the Netherlands show a good fit between the measured data (BHT and DST) and the conductive model. These encouraging results show that the assimilation of lithologically related parameters (radiogenic production and thermal conductivity) allow a relevant estimation of the temperature that can be used as a first order assessment of area of interest for geothermal systems. In addition, the interest relies in the identification of areas with misfit that can be further investigated with the relevant methodology.

3. PARIS BASIN

The Paris Basin is a bowl-shaped basin with a maximum thickness of just over 3km at its centre (SE of Paris). The continuous layers in the Paris Basin are Triassic to Quaternary with discontinuous Permo-Carboniferous sub-basins below. For the model, 6 layers have been selected and 494 corrected BHT values and 15 DST have been gathered.

3.1 Thermicity of the Paris Basin: modelling parameters

The methodology followed in the Paris Basin is similar to the method used for the Netherlands. The variable parameters to fit the temperature values (see below) are based on large-scale variations in the Lithosphere-Asthenosphere Boundary (LAB) depth and the smaller variation of the heat production in the Upper Crust. The entire lithosphere is considered with a fixed temperature of 1330ºC at the LAB. The layers in the lithosphere are the lithospheric mantle, lower Crust and upper Crust, each with thermal parameters assigned. The sedimentary description is done with 6 layers from the Triassic to Tertiary (Fig. 7). Each individual layer has been assigned a lithology that controls the thermal parameters (radiogenic heat production and thermal conductivity). The thermal conductivity (Fig. 8) takes into account the anisotropy of the required lithologies (e.g., shale).

In the Paris Basin two layers have a clearly identified regional-scale aquifers: the Keuper (Late Triassic) and the Dogger. The Keuper is of detritic composition and the Dogger is a carbonate reservoir.

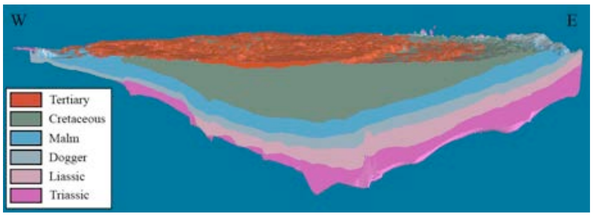

Figure 7: Layers in the Paris Basin along a E-W profile.

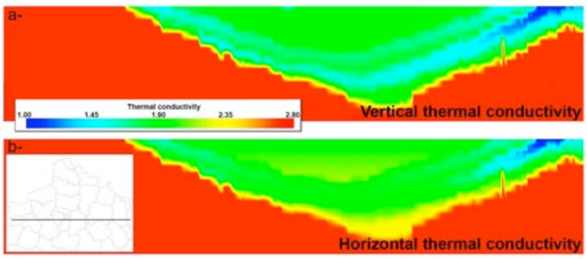

Figure 8: Thermal conductivity of the sedimentary layers along the E-W profile shown on figure 7.

The temperatures available in the Paris Basin are of two types: Bottom Hole Temperatures (BHT) and Drill Stem Tests (DST). The analytical method Instant Cylinder Source (ICS) has been assessed as being the most equilibrated correction method (Goutorbe et al, 2007). While the initial BHT gathered represented a total of 2443 measurements taken from across 459 wells, the final dataset has been reduced to 494 corrected BHT values. The average thermal gradient in the Paris Basin is 39.4ºC.km-1 with a fixed temperature of 10ºC at the surface.

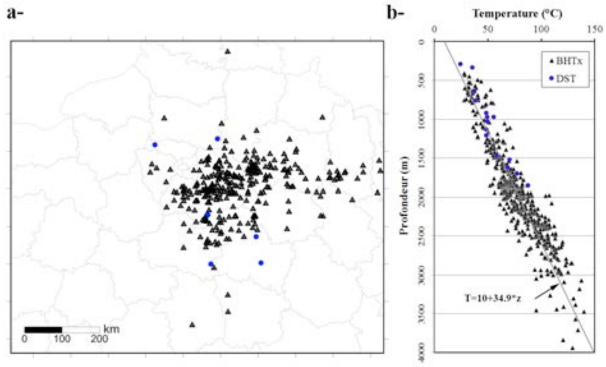

Figure 9: Temperature values available in the Paris Basin. a- map and b- temperature vs depth of the temperature values.

3.2 Thermicity of the Paris Basin: modelling results

The modelled temperature in the Paris Basin is presented as iso-depth maps in **figure 10**. The first point that should be noted is the main thermal repartition in each of the temperature maps presented. One important feature seems to be the visible difference on the maps between the iso-depths of 600m and 1000m, in comparison to the iso-depths of 2000m and 3000m. At 600m and 1000m, the temperature is noticeably higher at the border of the basin, and more precisely, at the south-east border of the Paris Basin. At a depth of 600m, the temperature reaches 30°C at the south-east corner of the basin and in the east of the basin. The geological map shows that these high temperature values are located in the Triassic, just below the insulating layers of the “Schistes Carton” of the Toarcian (i.e., one of the main components of the Liassic). This low conductivity is shown in Figure 8. The phenomenon is repeated at 1000m, but at this depth, the Toarcian base is geographically closer to the centre of the basin and the temperature is consequently modified.

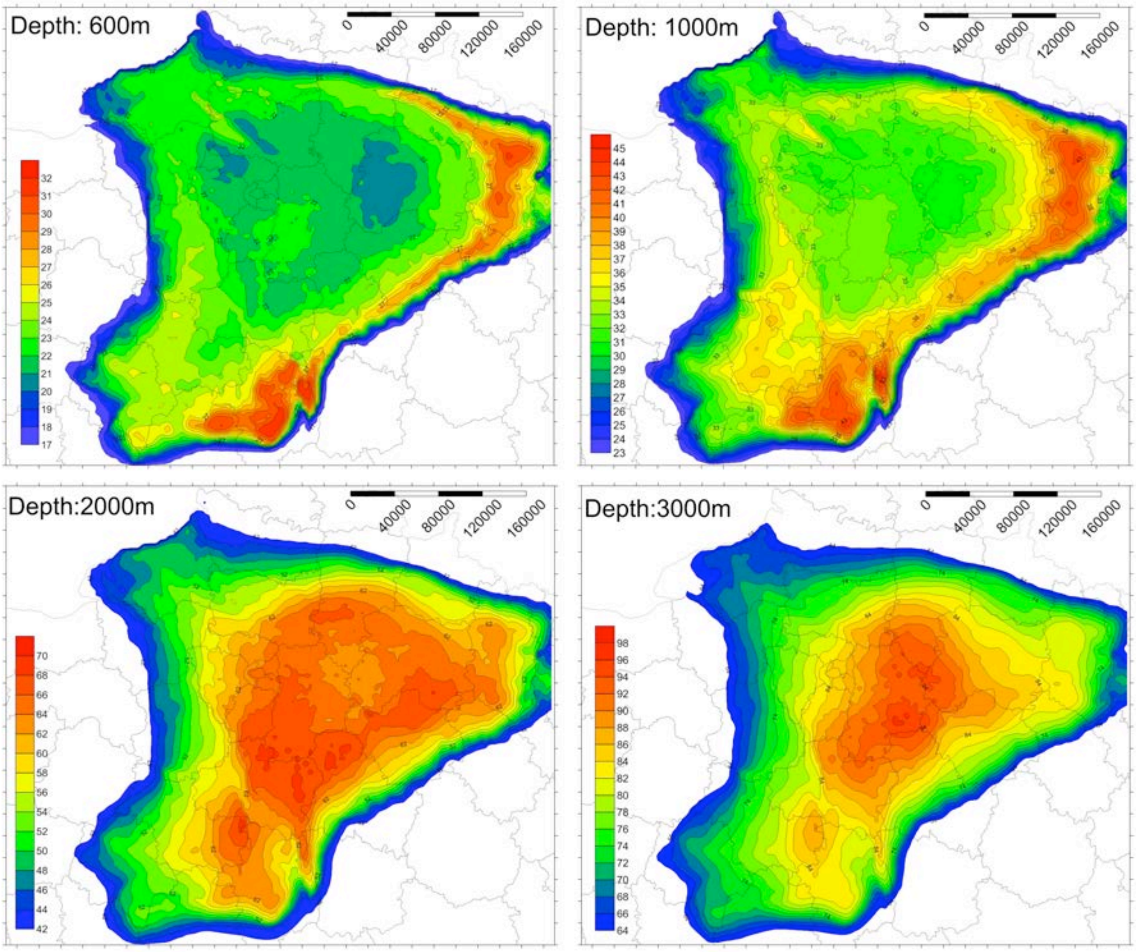

Figure 10: Isodepth temperature maps of the modelled temperature in the Paris Basin.

3.3 Thermicity of the Paris Basin: Influence of the basement

The influence on the temperature is not solely the result of the lithological variations in the sedimentary pile. The recent study of Baptiste et al (2016) shows that there is a continuity in the basement with the nearby Armorican Massif and the Massif Central. The first results of these studies are very promising as they show Permo-Carboniferous basins and substantial intrusions that could have a significant impact on the thermicity in the Paris Basin. The Permo-Carboniferous basins are also described in the recently published E-W profile in the Paris Basin (Gély and Hanot, 2014).

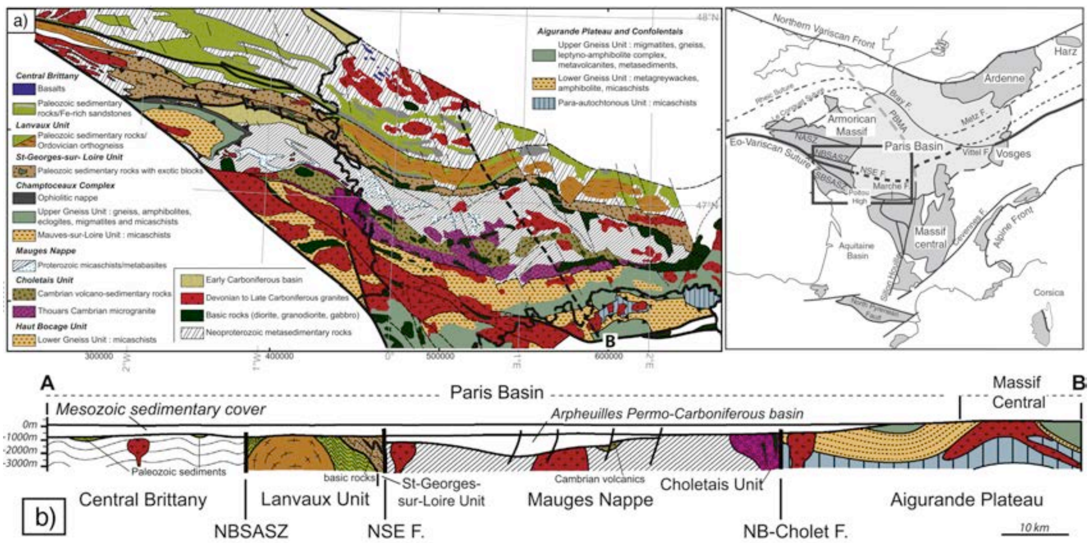

Figure 11: Geology of the basement in the SW of the Paris Basin.

3.4 Thermicity of the Paris Basin: results and discussion

The Paris Basin shows a strong impact of the lithology on the thermic structure. The geometry and the thermal conductivity related to the sediments have a regional impact on the temperature field in the basin. The new studies on the basement (any formation older than the Triassic) show a strong heterogeneity related to the Variscan orogeny and local Permo-Carboniferous sub-basins. The impact on the temperature could be of importance if the heat production (radiogenic granites) or the thermal conductivity (Permo-Carboniferous sub-basins) are significantly different.

4. CONCLUSIONS

The two examples presented here, of Paris Basin and the Netherlands, show the successful results of assessing regional temperature fields using tectonic-heat flow modelling. In both cases, two major components are important for the modelling: (1) the regional definition of the geological structure and composition of the sediments and (2) the gathered temperature measurements in the wells. In the Netherlands, the regional modelling has identified a temperature misfit not explained by the conductive model, while the work of Lipsey et al. (2016) has shown the local impact of fluid circulation. In the Paris Basin the strong impact of the Liassic "Schiste Carton" has been assessed and the ongoing work on the basement has offered us new opportunities for further understanding he temperature. From a geothermal energy point of view, both the Dutch and French models show regional areas of interest based on integrated modelling. In addition to these case-studies, it appears that modelling more specific works would be of great interest in understanding local temperature variation, which could in turn be used for the further development of geothermal energy systems.

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